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Extreme fluxes in solar energetic particle events: Methodological and physical limitations

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HIGHLIGHTS

- All available data on the largest solar proton events (SPEs) are analyzed.
- Distribution function obtained for 3 last cycles is confirmed for 41 solar cycles.
- Estimates of extremely large fluences in the past are found to be overestimated.
- Extremely large SEP fluxes are shown to obey a probabilistic distribution.
- Limitations are obtained for the extrapolation of the results to the past/future.

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ABSTRACT

In this study, all available data on the largest solar proton events (SPEs), or extreme solar energetic particle (SEP) events, for the period from 1561 up to now are analyzed. Under consideration are the observational, methodological and physical problems of energy-spectrum presentation for SEP fluxes (fluences) near the Earth's orbit. Special attention is paid to the study of the distribution function for extreme fluences of SEPs by their sizes. The authors present advances in at least three aspects: 1) a form of the distribution function that was previously obtained from the data for three cycles of solar activity has been completely confirmed by the data for 41 solar cycles; 2) early estimates of extremely large fluences in the past have been critically revised, and their values were found to be overestimated; and 3) extremely large SEP fluxes are shown to obey a probabilistic distribution, so the concept of an "upper limit flux" does not carry any strict physical sense although it serves as an important empirical restriction. SEP fluxes may only be characterized by the relative probabilities of their appearance, and there is a sharp break in the spectrum in the range of large fluences (or low probabilities). It is emphasized that modern observational data and methods of investigation do not allow, for the present, the precise resolution of the problem of the spectrum break or the estimation of the maximum potentialities of solar accelerator(s). This limitation considerably restricts the extrapolation of the obtained results to the past and future for application to the epochs with different levels of solar activity.

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1. Introduction

Long-term observations of solar proton events (SPEs), or solar energetic particle (SEP) events, have given a number of indications that approximately once during a given solar cycle, an event occurs whose fluence above a given energy (usually ≥10, ≥30, ≥60 and ≥100 MeV for protons) dominates the fluence of the entire cycle (e.g., Shea and Smart, 1990). It may overlap the fluences from the other events and even determine, in fact, a total fluence for the cycle. Such rare phenomena are sometimes called "rogue events" (Kallenrode and Cliver, 2001) in analogy to rogue ocean waves that have unusually large amplitudes. Well-known examples of rogue

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SEP events at the Earth occurred on 14 July 1959, 4 August 1972, 19 October 1989 and 14 July 2000. Rogue events have also been observed in the inner heliosphere – with *Helios* 1 on 4 November 1980 at 0.5 AU and with *Ulysses* in March 1991 at 2.5 AU. The origin of these rogue events is thought to be related to multiple coronal mass ejections (CMEs) and converging interplanetary shocks. If observed at the Earth's orbit, these rare extreme events become important geophysically and practically (e.g., radiation hazard for spacecraft).

In some cases, extreme SEP events in the non-relativistic energy range are accompanied by large fluxes of relativistic protons ($E_p \geq 500$ MeV), or solar cosmic rays (SCRs). They are usually registered by neutron monitors (NMs) at the Earth's surface (GLE phenomena, or Ground Level Enhancement of SCRs). Recently it was suggested (Crosby, 2009) that rare Solar Extreme Events (SEEs) be defined as those events in which the characteristics (field strength, speed, intensity of radiation, energies, etc.) of the associated phenomena (solar flares, CMEs, SEP events) are some orders of magnitude larger than those in most other events (e.g., the event of 20 January 2005).

At present, the so-called "Carrington event" of 1–2 September 1859 (Townsend et al., 2003, 2006) seems to be one of these "rare SEEs". As follows from Smart et al. (2006, 2007), the Carrington event (CE) had the largest integral fluence Φ of protons with energies of $E \geq 30$ MeV (i.e., the energy-integrated fluence above a certain energy value) in the approximately 450-year period starting in 1561. There is no doubt that the study of such rare events is of paramount importance. In particular, Townsend et al. (2003, 2006) have suggested that, henceforth, the CE, which had an integral fluence of $\Phi(\geq 30 \text{ MeV}) = 1.88 \times 10^{10}$ cm^{-2}, should be considered to be the best reference "worst case" for estimates of radiation hazard in space.

Indeed, the two nearest candidates for the role of the "worst case" – the events of 15 November 1960 and 4 August 1972 – were characterized by far lesser values of $\Phi(\geq 30 \text{ MeV})$, approximately 9×10^9 cm^{-2} and 5×10^9 cm^{-2}, respectively (Smart et al., 2006). Note, however, that those fluence values were calculated from data that were obtained in the epoch of historically fragmentary and indirect measurements of SEP fluxes. At the present time it has become clear that such early energy spectra have the analytical forms that are quite different from the spectral form that has recently been established (Nymmik, 2011c). For this reason, the fluence values for the events of 1960 and 1972 should be critically discussed in light of the new summary distribution function (see Section 2). Also of great interest are the estimation of the occurrence probabilities of such rare events at the present level of solar activity and the possible extrapolation of the obtained results to the remote past of the Earth (e.g., Wdowczyk and Wolfendale, 1977; Kiraly and Wolfendale, 1999).

As we know from our own long-term experience of studying solar cosmic rays, rare large solar events do not form some specific "class" of solar phenomena. They seem to constitute part of the common ensemble of SEP events because there is no sharp boundary between this "class" and the rest of the events. SEP events are described by a single distribution function, and SEEs naturally form its "tail" in the low probability range. This point of view has been confirmed, in particular, by the recent results of Crosby's (2009) analysis: SEEs are part of the global distribution of all events rather than "outliers" with their own special characteristics.

Our present study was greatly inspired by the publication of new data on proton fluences for a number of large events from 1561 to 1994 identified by the so-called nitrate method (McCracken et al., 2001) and by the results of the analysis and interpretation of those events (e.g., Townsend et al., 2003, 2006; Smart et al., 2006, 2007). At the same time, we relied upon our own experience of research in this field (e.g., Miroshnichenko, 1994, 1996, 2001; Nymmik, 1999a,b,c; 2007a,b,c). After providing a general Introduction to this paper (Section 1), we study the distribution function of proton fluxes with energies of ≥30 MeV (Section 2) and consider the possibility of its extrapolation to the range of flux magnitudes that are presently inaccessible to measurements with the level of solar activity taken into account. Furthermore (Section 3), we analyze the general features of the energy-spectrum shape for protons, methods for describing them and the relations between the spectral form and the event size.

Fluence energy spectra for a number of large SEP events are considered in Section 4 by drawing on the data from the Carrington event. Section 5 is devoted to the analysis of peak proton fluxes for extreme events that are comparable to the CE flux. Based on the above consistent approach to the presentation of the distribution function of SEP fluxes and the analysis of the peculiarities of their spectra, we also discuss here the maximum capabilities of solar accelerator(s), namely, we estimate the probabilities of generation (appearance) of extremely large fluxes of SCRs. In Section 6, we summarize our results and give a number of concluding remarks.

2. Distribution function of proton fluences

Distribution functions of SCR events with proton fluences of energy ≥30 MeV, or $\Phi(\geq 30 \text{ MeV})$, have been widely investigated (see, e.g., Nymmik, 2011c, and references therein). These functions are constructed, as a rule, based on the data from SEP events whose sizes are determined by measurements onboard the satellites of the *IMP* and *GOES* series. At present, the available data sets cover, depending on the selection criteria, approximately 200 events with $\Phi(\geq 30 \text{ MeV}) \geq 10^6$ cm^{-2} (Nymmik, 2011c). To describe the distributions, power-law functions are usually applied, sometimes with a break. This approach, however, allows us to calculate the occurrence probabilities of events with certain fluences only down to a probability of ~0.5% (~1/200), which is clearly insufficient for extreme estimates.

Lately, it has become obvious that the accumulation of new satellite data does not enable us to advance considerably in the determination of the form of the distribution function for SEP events as a function of their fluences in the range of low probabilities. An attempt to involve the data concerning cosmogenic isotopes in the lunar soil (Reedy, 1996), unfortunately, has not added any certainty in the resolution of this problem because the isotope data are related to the total (summary) flux of SCR protons with $E \geq 10$ MeV over the past ~10 My but not to individual SEP events.

Some progress on this problem was achieved when the data on the fluences of large SEP events for the period of 1561–1950 were obtained from Greenland ice cores (McCracken et al., 2001). These authors have succeeded, in particular, in estimating the proton fluence for the largest event of that period, namely, the Carrington event, which occurred on 1–2 September 1859; its value was $\Phi(\geq 30 \text{ MeV}) = 1.88 \times 10^{10}$ cm^{-2}. Nevertheless, even those data proved insufficient to determine the form of the distribution function in the total diapason of changes of the fluence $\Phi(\geq 30 \text{ MeV})$. In fact, from those data it was impossible to determine the number of small events that constitute the initial part of the distribution function in the range of fluences $\Phi(\geq 30 \text{ MeV}) = 10^6 \div 3 \times 10^9$ cm^{-2}.

Therefore, to calculate the probabilities of extra-large SEP events (and the distribution function) from polar-ice data, it is necessary to know how many single events of fluence $\Phi(\geq 30 \text{ MeV}) \geq 10^6$ cm^{-2} have occurred from 1561 up to the present. In our opinion, the solution to this problem seems to be available.

Previously, we have repeatedly demonstrated (e.g., Nymmik, 1999a, 2006, 2007a,b,c) that the occurrence rate of SCR events with fluence $\Phi(\geq 30\text{ MeV}) \geq 10^6\text{ cm}^{-2}$ is, on average, proportional to the solar-activity (SA) level expressed as the annual number of sunspots. A similar tendency has been found by Miroshnichenko (2001, Fig. 10.12) in behavior of the yearly mean numbers of >10 MeV proton events at the intensity threshold >1 pfu in comparison with the level of SA for the period of 1955–1996 ($1\text{ pfu} = 1\text{ p cm}^{-2}\text{ s}^{-1}\text{ sr}^{-1}$). In other words, the mean number of SEP events, n, that occurred within a given time interval ($T_1 \div T_2$) is proportional to the annual sum of the sunspot numbers ΣW_i:

$$n = k \cdot \sum_{T_1}^{T_2} W_i \quad (1)$$

here $k = 0.083$, and W_i are the smoothed annual mean-monthly sunspot numbers. Therefore, for the total number of single SEP events N for the period from T_1 to T_2 (1561 ÷ 2008), we have:

$$N = n \cdot \left(\sum_{1561}^{2008} W_i / \sum_{1973}^{2008} W_i \right) \quad (2)$$

where $n = 205$ is the number of SEP events with a fluence of $\Phi(\geq 30\text{ MeV}) \geq 10^6\text{ cm}^{-2}$ in 1973–2008. Therefore, to obtain a rough estimate of the N value for the period of 1561–2008, it is sufficient to determine the number of sunspots that occurred during that time. The sunspot annual sums have been taken from two sources. From 1700 to the present the sunspot data can be found at the NOAA page (http://www.ngdc.noaa.gov/stp/Solar/ftpsunspotnumber/html). Before 1700, the sunspot numbers were estimated by Nagovitsyn (2006). From those data, we find: $\sum_{1973}^{2008} W_i = 2340$ and $\sum_{1561}^{2008} W_i = 19930$. Thus, substituting these sums into Eq. (2), we find the number of SEP events with proton fluence $\Phi(\geq 30\text{ MeV}) \geq 10^6\text{ cm}^{-2}$ in the period of 1561–2008 to be $N = 1746$.

In addition to the Carrington event, from the same data by McCracken et al. (2001), we have also estimated the probabilities for several proton events with extremely large fluences. One of them, with a fluence of $\Phi(\geq 30\text{ MeV}) = 1.11 \times 10^{10}\text{ cm}^{-2}$, occurred in 1895. It should be noted that 10 events in the period of 1561–1950 had fluences in the interval of $6.1 \times 10^9 \leq \Phi(\geq 30\text{ MeV}) \leq 10^{10}\text{ cm}^{-2}$. Therefore, for $\Phi(\geq 30\text{ MeV}) \geq 1.88 \times 10^{10}\text{ cm}^{-2}$, we have only one event; for $\Phi(\geq 30\text{ MeV}) \geq 1.00 \times 10^{10}\text{ cm}^{-2}$, there are two events and for $\Phi(\geq 30\text{ MeV}) \geq 6.1 \times 10^9\text{ cm}^{-2}$, we have 12 events in total. The results of our estimates are summarized in Fig. 1.

To approximate the fluence data (Fig. 1), we applied a function that was obtained by Nymmik (1999b):

$$\Psi(\geq \Phi) = \left(\frac{\Phi}{10^6} \right)^{-\gamma} / \exp(\Phi/\Phi_0) \quad (3)$$

where γ is a power-law index, $\Phi \equiv \Phi(\geq 30\text{ MeV})$, and Φ_0 is the characteristic exponential constant. As was shown by Lu et al. (1993), such a form of the distribution function seems to be universal for the description of many manifestations of solar flares (peak fluxes and/or energy fluences in X-ray and radio-wave bursts, in proton and electron emissions, etc.). The solid line in Fig. 1 depicts the approximation to the data obtained in the form of Eq. (3).

The approximation of the event distribution (Fig. 1) with the function (3) on the data of events with fluences $\Phi(\geq 30\text{ MeV})$ proved to be reasonable with the following parameters: $\gamma = 0.32$ and $\Phi_0 = 7 \times 10^9\text{ cm}^{-2}$. Note that these parameters are, in practice, identical to those obtained previously from analysis of the events measured only onboard the satellites (e.g., Nymmik, 1999b, 2011c).

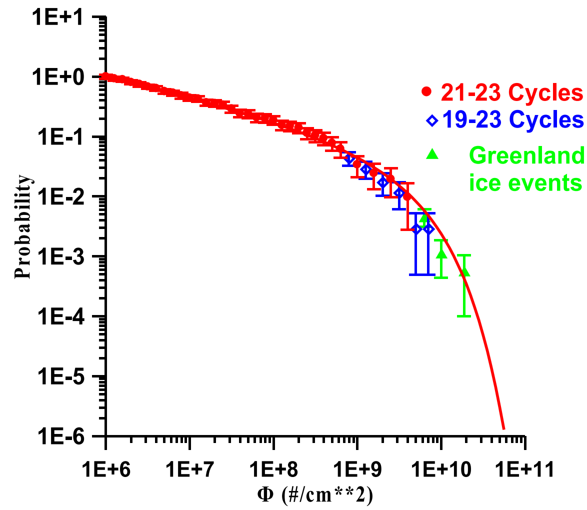

Fig. 1. Distribution of SEP events as a function of the integral fluences of $E \geq 30$ MeV protons determined from measurements onboard the two satellites *IMP*-8 and *GOES* (measurements from solar cycles 21–23 are indicated by the red points and the large events of cycles 19–23 are indicated by the blue diamonds) and from Greenland ice-core data for the pre-space era (green triangles). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

For instance, in the paper by Nymmik (1999b) the value of $\Phi_0 = 6 \times 10^9\text{ cm}^{-2}$ was obtained.

The applicability of the method suggested above for the construction of the distribution function has been demonstrated in Fig. 1 for the periods in which regular monitoring of SEP events was completely absent. Obviously, our approach may also be applied to the event ensemble that was registered in solar cycles 19–20. As mentioned in Section 1, in spite of the absence of regular SEP measurements during that period, important data were obtained on some extreme events (e.g., 23 February 1956, 10 and 14 August 1959, 12 November 1960 and 4 August 1972, all data are taken from Shea and Smart, 1990). Specifically, for cycles 19–23, we find that the sum of sunspot numbers is $\sum_{1954}^{2008} W_i = 3950$.

With this estimate for the total period of 1954–2008 (including the epoch of early satellite SEP measurements), we find that the number of SEP events with proton fluence $\Phi(\geq 30\text{ MeV}) \geq 10^6\text{ cm}^{-2}$ is $N = 346$. Therefore, the event with the maximum fluence $\Phi(\geq 30\text{ MeV}) = 9 \times 10^9\text{ cm}^{-2}$ in that period (12 November 1960) had a probability to occur of approximately 2.9×10^{-3}. Data on some other large SEP events of solar cycles 19–20 were added to available large-event data of cycles 21–23. These results, which are also presented in Fig. 1, are fully consistent with the other data that forms the base of the distribution function.

In particular, the probability of the Carrington event obtained from (3) is $P = 5.7 \times 10^{-4}$. For the two SEP events from the data of McCracken et al. (2001) with $\Phi(\geq 30\text{ MeV}) \geq 1.00 \times 10^{10}\text{ cm}^{-2}$ we find $P = 1.15 \times 10^{-3}$, and for $\Phi(\geq 30\text{ MeV}) \geq 6.31 \times 10^9\text{ cm}^{-2}$ (12 events) the occurrence probability is $P = 5.7 \times 10^{-3}$. As follows from Fig. 1, an event with a fluence of $\Phi(\geq 30\text{ MeV}) \geq 6 \times 10^{10}\text{ cm}^{-2}$ may occur within the total collection of $\sim 10^6$ events with $\Phi(\geq 30\text{ MeV}) \geq 10^6\text{ cm}^{-2}$. Therefore, at the present level of solar activity, we would expect that the occurrence of such an event would require approximately 2.6×10^5 years, if we consider (see above) that during the period of 447 years (1561–2008), in total, 1746 SEP events with $\Phi(\geq 30\text{ MeV}) \geq 10^6\text{ cm}^{-2}$ have presumably occurred.

3. Energy spectra of SEP events

To estimate the energy spectra of extreme events it is necessary, first of all, to establish the actual functional shape of the SEP spectra and their characteristic features. At the present time, experimentalists have succeeded in measuring SEP spectra in much broader energy ranges than before, namely, in the intervals of 0.32 ÷ 500 MeV for protons and 0.035÷168 MeV/nucleon for heavy ions (for example, for Fe ions). From this new spacecraft data it has become clear that SEP spectra form two segments that may be approximated by two power-law functions, with an intermediate break-point (or bend-point, "knee") at a typical energy of $E_b \approx 30$ MeV (e.g., Mewaldt et al., 2005a,b, 2007, 2009; Nymmik, 2011a). Such a double power-law (or two-segment) shape seems to be consistent with spectrum "turnover" that follows from the theoretical model of Ellison and Ramaty (1985) for the case in which particles are accelerated by shock waves. In this publication the authors proposed "an exponential turnover of the power-law spectrum":

$$\frac{dF}{dE} = C \cdot E^{-\gamma} \cdot \exp\left(\frac{E}{E_0}\right) \tag{4}$$

As two characteristic examples, Ellison and Ramaty (1985) have plotted the proton spectra for the events of 7 and 21 June 1980 (Fig. 2). As one can see from Fig. 2, these two events were rather small. As a result, their proton fluxes could be measured only in limited energy range (from approximately 2 MeV through 200 MeV). The pairs of characteristic spectral parameters for the events of 7 and 21 June 1980 were $\gamma = 2.1$ and $E_0 = 20$ MeV for the event of 7 June 1980 and $\gamma = 2.3$ and $E_0 = 30$ MeV for the vent of 21 June. Note that these characteristic energy values are close to the proposed value of the typical mean break-point energy in the proton spectra $E_b \approx 30$ MeV (Mottl et al., 2001a,b).

As has been shown (Mottl et al., 2001a,b), above the energy of 30 MeV, all data concerning peak proton fluxes, without any exceptions, are described by power-law functions of particle momentum p (or magnetic rigidity R, in the case of protons), without any signature of exponential turnover:

$$F(E)dE = F(p)\frac{dp}{dE}dE = C \cdot \left(\frac{p}{p_b}\right)^{-\gamma} \cdot \frac{dE}{\beta} \tag{5}$$

where $\beta = p/\sqrt{p^2 + m^2}$ is the relative particle velocity,$p = \sqrt{E(E + 2mc^2)}$ is the particle momentum and p_b is the particle momentum value in the "knee" or "bend" region. According to our estimates, the energy $E_b = 30$ MeV is simply the mean

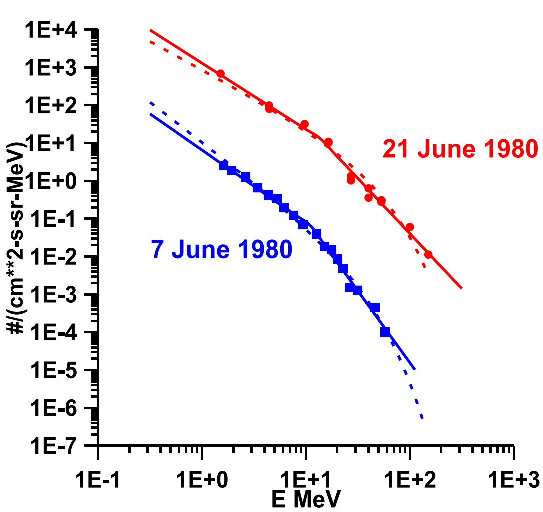

Fig. 2. Differential intensity vs. proton energy for the events of 7 and 21 June 1980 from *IMP*-8 data (squares and points, respectively); dashed lines – estimates using (4) (Ellison and Ramaty, 1985); solid lines – our approximation using a double power-law function (5).

position of the "break-point" of the proton spectra of powerful events. With this approach, the spectral indices of the double power-law functions below ($\gamma = \gamma_1$) and above ($\gamma = \gamma_2$) the break-point satisfy the requirement $\gamma_1 \le \gamma_2$. It would not be out of place to observe that a difference between the power-law spectra in terms of energy and momentum when approximating the flux magnitudes in the range of non-relativistic energies ($E < 500$ MeV) by no means affects the results of Mewaldt et al. (2005a,b, 2007, 2009) and Nymmik (2011a), including the break-point position.

Our estimates of the root mean square (r.m.s.) deviations show that the approximation of the spectra for the events of 7 and 21 June 1980 with double power-law functions results in statistical errors of, respectively, 1.5 and 2.1 times less than the approximation using (4). It should be noted that in all papers that apply Formula (4), in fact, the SEP spectra in the authors' published figures may be approximated more accurately by two segments of power-law functions. In particular, in our analysis (Nymmik, 2011b) of heavy-ion fluxes for 28 SEP events measured by the SIS detector onboard the *ACE* spacecraft at energies ≥5 MeV/nucleon, we found no signatures of the expected "turnover" in the form of an exponential factor.

It is timely to note that in our earlier works (Mottl et al., 2001a,b) we have analyzed the particle fluxes for 13 SEP events that were forestalled by GLEs – Ground Level Enhancements of SCRs. The analysis was carried out on the observational data for 13 GLEs of solar cycle 22. These data were obtained by three satellites (*IMP*-8, *Meteor*, and *GOES*), stratospheric balloons and surface neutron monitors, and they have been summarized in the Catalogue of Solar Proton Events (1987–1996) by Sladkova et al. (1998).

From the above considerations it follows that in spite of seven decades of SCR studies, the debate still continues in the literature on the true form of the spectrum at the source (at/near the Sun) and on the dynamics of spectrum formation. This situation may be partially explained by the development of new models of SEP generation based on the concept of multiple acceleration of charged particles at the Sun (in flares) or near the Sun (at CME-driven shocks) (e.g., Miroshnichenko and Perez-Peraza, 2008). With this concept in mind, to advance the understanding of the physics of these acceleration processes we must return to some primary concepts and models ("first principles") from which the studies of SCR physics began.

Many years ago, based on the results of the analysis of observed spectra, Miroshnichenko et al. (1973) suggested a semi-empirical "dynamic" model of source spectrum formation. Later on, guided by this model (Miroshnichenko, 1977, 1983, 1990), it was shown that there is a certain relation between the hardness/steepness (index γ) of the SCR spectrum at the source and the flare power (energetics). More exactly, there is a relation between the γ value and the magnitude of the electric field E_e in the region of magnetic reconnection. The effect reduces to a decrease in the steepness of the spectrum with increasing E_e, mainly in the low-energy range (the spectrum becomes flatter, i.e., harder).

According to this model, the source spectrum may be formed by a simple combination of acceleration by the direct electric field E_e in the reconnection region and betatron acceleration with a characteristic time τ_a. To clarify some details, we refer to the resulting source spectrum

$$D(R) = D_0(1 + R/R^*)^{-\gamma} \tag{6}$$

where D is the total number of accelerated particles of rigidity R (or energy E), D_0 is a normalization constant, and $R^* = cE_e\tau_a$ is an empirical rigidity parameter connecting the two acceleration mechanisms. The differential power-law index is $\gamma = 1 + \tau_a/\tau_c$, where c is the speed of light and τ_c is the characteristic time of particle confinement in the source.

As follows from (6), the spectral properties and, in general, the dynamics of source-spectrum formation are determined by the ratios between the characteristic parameters of the acceleration mechanisms. This may be visually seen in Fig. 3, where we present the results of the calculations of three spectra (curves 1–3 in relative units $D(E)/D_0$, left and bottom scales). In these calculations, instead of the unknown value of E_e, we used the parameter $R^* = cE_e\tau_a$ (in rigidity units, MV) of the model (Miroshnichenko, 1977, 1983). The calculations were carried out for the following parameter values: $\gamma = 5.5$, $R^* = 0.1$ GV (curve 1); $\gamma = 5.5$, $R^* = 0.5$ (curve 2); and $\gamma = 3.5$, $R^* = 0.5$ GV (curve 3), with a constant $D_0 = 1.0$.

As was to be expected, the source-energy spectrum has a changing slope that may be compared to the exponential turnover obtained by Ellison and Ramaty (1985) in their model of shock acceleration. Note also that if the value of E_e (or, more exactly, the parameter R^*) changes by a factor of 5 (cf. curves 1 and 2) the number of accelerated particles $D(E)/D_0$, for example, at an energy of 100 MeV will be changed by 2.5 orders of magnitude. In this dynamical picture of SCR acceleration, obviously, the spectral slope (index γ) and the number of accelerated particles (source spectrum as a whole) are affected by the parameter R^* most strongly in the low-energy range.

Curves 4–6 in Fig. 3 (left and top scales) demonstrate a dependence of the numbers $D(E)/D_0$ of accelerated particles at a given energy E on the value of the parameter R^*. The calculations were carried out for the following sets of parameters: $E = 1000$ MeV, $\gamma = 5.5$ (curve 4); $E = 100$ MeV, $\gamma = 5.5$ (curve 5); and $E = 100$ MeV, $\gamma = 3.0$ (curve 6). Again, it may be seen that the parameter R^* most strongly affects the values of $D(E)/D_0$ in the low-energy range.

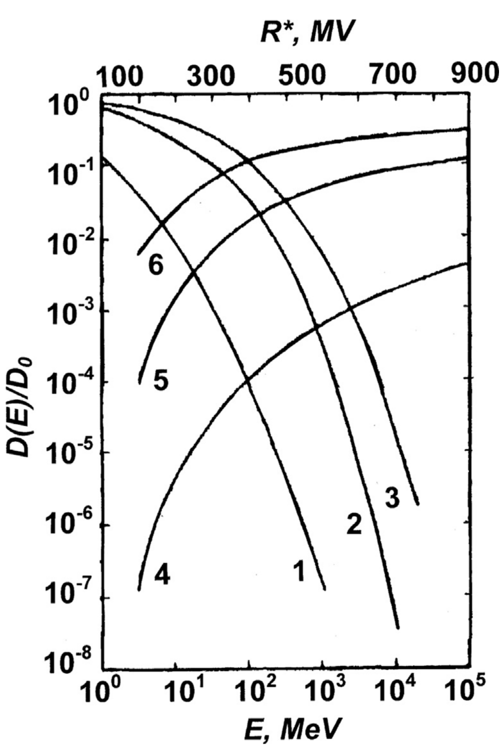

Fig. 3. Differential energy spectra of protons at the source (curves 1–3, left and bottom scales) and numbers of accelerated particles $D(E)/D_0$ vs. electric field E_e (or parameter R^* in units of MV) in the region of magnetic reconnection (curves 4–6, left and top scales); adapted from Miroshnichenko (1983, 1990).

If we attempt to approximate the calculated spectra with power-law functions of energy E with a break-point at some energy E_b, the intensity of the particles at energy E_b and even the position of the knee (i.e., the E_b value) will clearly be displaced along the intensity and energy axes, respectively, depending on the power of the acceleration mechanisms (we call this effect “spectrum swelling”, see curves 1–3 in Fig. 3). Moreover, the value of E_b (i.e., the position of the break-point) will be slightly changed from one event to another. Hence, the number of particles at a given energy, their fluence and the mean value of the knee energy will depend on the source power and the total number of accelerated particles in the event. This conclusion does not contradict the typical spectral picture of SEP events (e.g., Fig. 2).

Recently, from the data of the particle detector ULEIS onboard the *ACE* spacecraft and two particle detectors onboard the *GOES* satellites, we have estimated the values of the knee energy in the spectra of the integral fluences of 51 gradual SEP events of the solar cycle 23. The method and details of analysis are described elsewhere (Nymmik, 2012). Our results (Fig. 4) demonstrate a distinct tendency for the knee's break-point energy E_b to increase as the event power – or, more exactly, the proton fluence $\Phi(\geq 30$ MeV) – increases.

From the data depicted above (Figs. 2–4) it follows that all “weak” SEP events seem to be characterized by a more “slack” development of the acceleration process as compared with powerful events. We are inclined to consider this to be a confirmation of the so-called “Big Flare Syndrome” (BFS) that was proposed by Kahler (1982).

According to this empirical phenomenological concept, all energetic flare phenomena, statistically, are more intense in larger flares, regardless of the detailed physics of the processes involved. In other words, all eruptive event emissions (in this case the SEP fluences and the associated peak flare fluxes) tend to scale together. In our opinion, this heuristic concept forms the start of a new understanding of the flare-CME dilemma. Moreover, at our modern level of knowledge of the topological and physical links between flares and CMEs, this concept may be extended to the “SEE syndrome”, as suggested by Crosby (2009).

4. Energy spectra of proton fluences in extreme large events

The recent new information on the Carrington event (Townsend et al., 2003, 2006), unfortunately, is limited to the magnitude of the

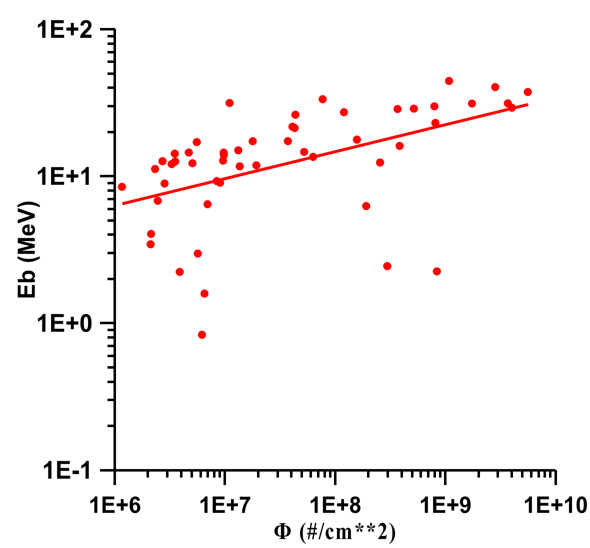

Fig. 4. Break-point energy in the spectra of the integral proton fluences of gradual SEP events vs. event size for $\Phi \equiv \Phi(\geq 30$ MeV) (present work) from the data summarized in Nymmik (2012).

proton fluence at the energy ≥30 MeV only; the fluence values at other energies (the full energy spectrum) remain unknown. Below we attempt to estimate the spectral shape and the fluence magnitudes that may be present in the other cases that are as rare as the Carrington event. For this, we proceed from two assumptions: 1) the main parameter of the SEP energy spectrum – its slope for energies above the knee – does not depend on the level of SA (Mottl and Nymmik, 2001), and 2) the mean energy of the knee E_b increases only relatively faintly as the SEP event size increases (Fig. 4).

Such assumptions seem to be quite correct for the limited range of non-relativistic energies and for the limited number of SEP events. Furthermore, by analogy it will be not very difficult to construct an averaged integral spectrum of fluences that should be similar to the spectra of the fluences of lesser magnitudes. The corresponding sequence of procedures is illustrated in Fig. 5 with the data of the 3-day proton fluences with energies from 0.32 to 500 MeV from the large event (GLE59) of 14 July 2000 (the Bastille Day Event, or BDE).

In the course of our calculations it has become clear that the proton fluence $\Phi(\geq 30\ \text{MeV})$ for the BDE seems to be approximately $4.46 \times 10^9\ \text{cm}^{-2}$, that is, a factor of 4.22 times less than that for the Carrington event, $\Phi(\geq 30\ \text{MeV}) = 1.88 \times 10^{10}\ \text{cm}^{-2}$. By multiplying the fluxes of the BDE by this factor we obtain a tentative version of the integral fluence spectrum for the Carrington event (Fig. 6). When proceeding from the spectra of other events, one can obtain different versions of the integral fluence spectrum.

With this goal, we used the data of five SEP events: 8 November 2000, 24 September and 4 November 2001, 28 October 2003 (GLE65) and 17 January 2005 (GLE69). These events proved to be the largest ones for the entirety of solar cycle 23 in terms of the size of the fluence $\Phi(\geq 30\ \text{MeV})$. By averaging the fluences for all these events and calculating the corresponding r.m.s. deviations, we have obtained a differential energy spectrum for the expected fluences of the Carrington event (Fig. 7). This Figure also depicts some widely used energy spectra of fluences constructed by compiling the data of powerful SEP events in February 1956, November 1960, and August 1972 (Wilson et al., 1999).

It is not out of place to emphasize once more that in the case of Fig. 7, the main reason for the extrapolation of the spectrum to the

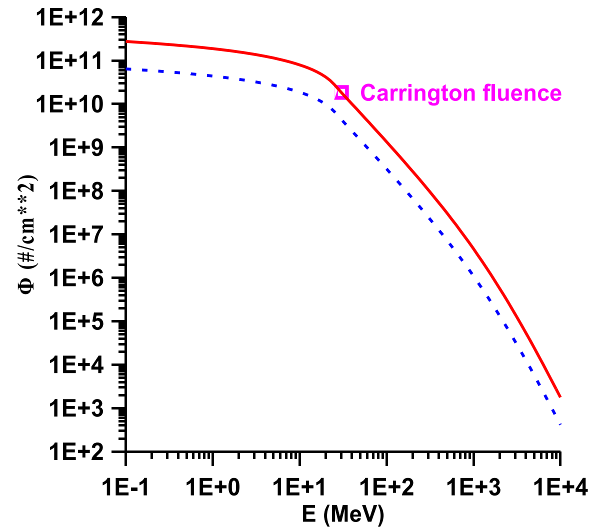

Fig. 6. Integral energy spectrum of the proton fluences for the event of 14 July 2000 (dashed line) and a similar model spectrum for the Carrington event (solid line).

energy of 10.6 GeV (GLE42 on 29 September 1989) is to serve the results of our earlier studies (Mottl et al., 2001a,b). This event was selected because the GLE42 proved to be the most intensive event in the relativistic energy range for solar cycle 22. According to the comprehensive data (including the records of neutron monitors) compiled in the Catalogue of SPEs of 1987–1996 by Sladkova et al. (1998), the GLE42 spectrum was determined at least up to energies ≥10 GeV.

The comparison of the fluence spectra calculated for the Carrington event with the spectra for the historical events presented in Fig. 7 demonstrates extremely rough character of early fluence data. In our opinion (Nymmik, 2011c), this is caused by rather inadequate procedures for the selection and processing of data obtained by different detectors and methods in the past. In particular, the more than doubtful overestimation of the fluences for the event of 23 February 1956 in the proton-energy range of $E \geq 200$ MeV should be noted. For this reason, we cast serious doubt on the shape of those energy spectra above $E_p \geq 30$ MeV. At the

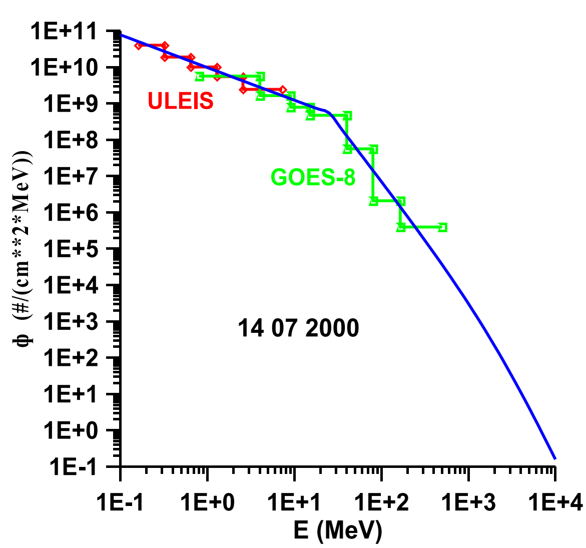

Fig. 5. Differential energy spectrum (broken lines) of the proton fluences of $\Phi \equiv \Phi(\geq 30\ \text{MeV})$ estimated from the measurements onboard two spacecraft – *ACE* (ULEIS detector) and *GOES*-8 (Telescope and DOME). The solid line is the approximation and interpolation of the data with (5).

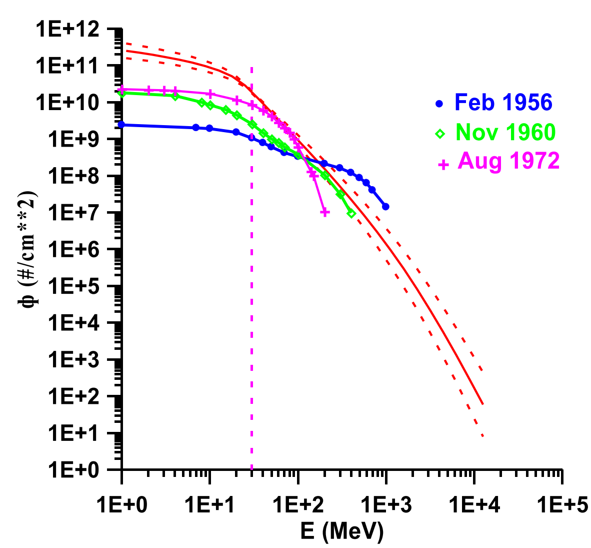

Fig. 7. Energy spectra of the proton fluences for the Carrington event (solid line) with the expected maximum and minimum r.m.s. deviations (dashed lines). Also shown are similar spectra for large SEP events in February 1956, November 1960 and August 1972 (Wilson et al., 1999). The vertical dashed line marks the values of fluences $\Phi(\geq 30\ \text{MeV})$.

same time, we conditionally assume the eventual use of the fluences $\Phi(\geq 30$ MeV) for those events if the fluences may be obtained from independent sources (Fig. 1) whose energy spectra differ from those presented in Fig. 7.

Note once more that the proton fluxes that may be described, on average, by the spectrum of the Carrington event, appear approximately once in a period of 450 years (see Fig. 1 and Eq. (2)). In other words, approximately one such flux might be expected to appear among the 1746 total expected events with a fluence of $\Phi(\geq 30\ \text{MeV})\geq 10^6$ cm^{-2} during such a time period. Meanwhile, for the past several decades, during every 11-year cycle of solar activity, we have observed between 50 and 100 events with a fluence of $\Phi(\geq 30\ \text{MeV})\geq 10^6$ cm^{-2}.

5. Energy spectra for peak proton fluxes

A similar method was also applied to estimate the spectra for the peak proton fluxes (or peak spectra) in SEP events comparable to the Carrington event. We used the same five SEP events as we did for the analysis of the fluence spectra. The spectrum of the peak fluxes is the integral energy spectrum of the maximum fluxes (intensities) of particles above a certain energy value. This spectrum is constructed with the time-of-maximum (TOM) intensities $I(>E_p)$ for different energy thresholds (e.g., Miroshnichenko, 2001, Fig. 4.4; Miroshnichenko and Perez-Peraza, 2008, p.95).

The peak fluxes are calculated from the data of the ULEIS (*ACE*) and Telescope and DOME (*GOES*) detectors. Furthermore, each of their energy spectra is presented in the form of a power-law momentum function with a knee. The calculated fluxes have been multiplied by the same factors as in the previous case for the fluences. Again, all five peak spectra obtained with this procedure for the Carrington event have been averaged; also, their r.m.s. deviations have been estimated (Fig. 8).

In Fig. 8 we also reproduce the integral "upper-limit spectrum" (ULS) for the peak SEP fluxes suggested by Miroshnichenko (1994, 1996). The ULS may be fitted with a power-law function with an integral exponent that depends on the proton energy, namely, $\gamma = \gamma_0 E^{\alpha}$, where $\alpha = 0.1$ and $\gamma = 1.0$ for $E_p > 1$ MeV. The rest of the parameters of the ULS are given in Table 1. The uncertainties of the exponent values are estimated to be ± 0.2 and ± 0.5 at energies $<10^9$ eV and $>10^{10}$ eV, respectively.

Table 1
Parameters of the upper-limit spectrum (ULS) for SCRs (Miroshnichenko, 1996, 2001).

Energy E_p, eV	Exponent, γ	$I(>E_p)$, pfu
$>10^6$	1.00	10^7
$>10^7$	1.45	10^6
$>10^8$	1.65	3.5×10^4
$>10^9$	2.20	8.0×10^2
$>10^{10}$	3.60	1.2×10^0
$>10^{11}$	>4.00	7.0×10^{-4}

From these data it follows that the limit peak flux at energy ≥ 30 MeV exceeds the expected size of the peak flux from the Carrington event by a factor approximately 7.2. Taking into account this empirical factor, under the assumption on the validity of the calculated spectrum for peak fluxes of the Carrington event, the "upper-limit spectrum" of Miroshnichenko (1994, 1996) may be corrected (dashed blue line). It remains only to establish the extent of the reliability for such "limit fluxes", i.e., to investigate with what probability such limit fluxes are reached.

With this goal in mind, we again applied an interpolation of the distribution function (3) into the range of extremely low probabilities. To do so, it was assumed that the peak fluxes and fluences for a large ensemble of SEP events are, on average, proportional to one another. Our estimates are based on the measurements onboard the spacecraft *IMP*-8 and *GOES* and on the data from the Greenland ice cores. We also have taken into account the integral fluences of $\Phi(\geq 30$ MeV) estimated from the data of Kiraly and Wolfendale (1999), which have been extrapolated into the past for 1 My and 100 My. Our final results are presented in Fig. 9.

The data shown in Figs. 8 and 9 provide some evidence of that a "limit event" of the type predicted by Miroshnichenko (1994, 1996) would have a fluence $\Phi(\geq 30$ MeV) of approximately 2×10^{11} cm^{-2}. The probability of the occurrence of such an event amongst the

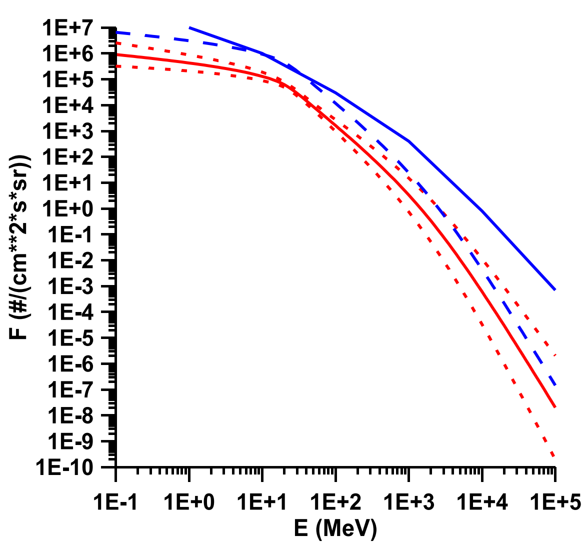

Fig. 8. Average integral peak proton-flux energy spectrum F for the Carrington event (red line with dashed r.m.s. deviations). Solid blue line – Upper-Limit Spectrum (ULS) for SCRs (Miroshnichenko, 1994, 1996); dashed blue line – corrected ULS (present work). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

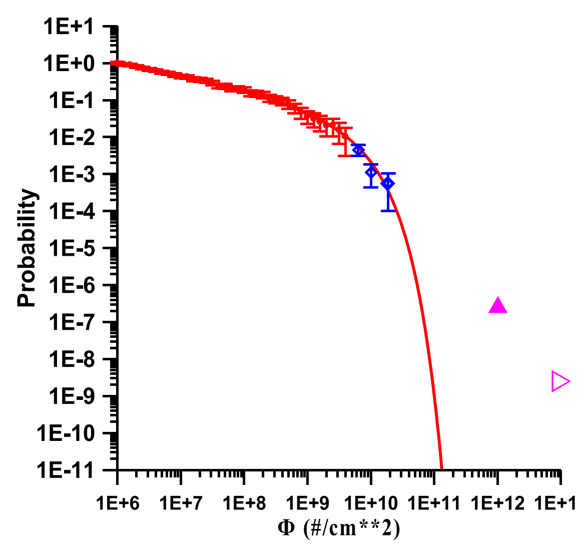

Fig. 9. Distribution function of SEP events as a function of the integral fluences of $\Phi \equiv \Phi(\geq 30$ MeV), including the range of very small probabilities. Our estimates are based on the measurements taken onboard the two spacecraft *IMP*-8 and *GOES* (points) and on the data from the Greenland ice cores (blue diamonds); solid red line represents the distribution function (3). The full and open triangles demonstrate the extrapolation of the integral fluences of $\Phi(\geq 30$ MeV) estimated in the present work from the data of Kiraly and Wolfendale (1999) into the past for 1 My and 100 My, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

events with fluences of $\Phi(\geq 30\ \mathrm{MeV}) \geq 10^6\ \mathrm{cm}^{-2}$ is $P = 10^{-11}$. This is extremely small, but it is a well-defined quantity. Obviously, at the present level of our knowledge, it may be called a "limit probability" only highly conditionally.

It is appropriate to acknowledge, however, that the ULS was constructed on the condition that all its points are situated approximately one order of magnitude above the largest observed (or estimated) values of the integral proton intensity at each energy threshold. The factor $\sim$ 10 was chosen to provide the necessary "reserve" of particle intensity for overlapping the established or assumed range of uncertainties in the measured (estimated) values of the peak flux (Miroshnichenko, 2001). Taking this "reserve" into account, we obtain more realistic estimates of the peak intensity $I(>30\ \mathrm{MeV}) = 7.15 \times 10^3$ pfu and the ULS fluence $\Phi(\geq 30\ \mathrm{MeV}) \approx 2 \times 10^{10}\ \mathrm{cm}^{-2}$, that are, in practice, consistent with the data obtained for the Carrington event (Fig. 8). Therefore, the empirical ULS model suggested by Miroshnichenko (1994, 1996, 2001, Fig. 4.4) has anticipated, in fact, the SEP observational situation, at least in the range of extremely large fluences.

In the context of this study, the estimates of the proton fluences at other energies (besides 30 MeV) also deserve serious attention, especially, for the understanding of the flare (proton) activity of the Sun in the remote past. Many years ago, Wdowczyk and Wolfendale (1977) addressed the question of the long-term frequency of large solar energy releases in the form of SCRs or SEPs and their possible effects, as compared with other catastrophic events. The main body of their work appears to remain valid, although some details have changed. The very flat integral power-law fits (logarithmic slope of approximately -0.5) suggest that several dramatic solar energy releases should be expected in geologically short times, if the trend continues.

Extrapolating their highest-energy (>60 MeV) fit to long time scales, Kiraly and Wolfendale (1999) have obtained some other estimates. It turns out that while the highest fluence measured prior to 1999 (within approximately 30 years) was $3 \times 10^9\ \mathrm{cm}^{-2}$, one would expect a few events above $10^{12}\ \mathrm{cm}^{-2}$ in 1 My, and in 100 My, one would expect a few above $10^{13}\ \mathrm{cm}^{-2}$. This is far less than one would expect from the flat slopes found by Wdowczyk and Wolfendale (1977), but still approximately two orders of magnitude higher than what follows from our estimates.

In fact, according to modern data concerning proton fluences at energies $\geq$30 MeV, for the period from 1973 up to 2008, 205 events were registered with the fluences $\geq 10^6\ \mathrm{cm}^{-2}$ (Nymmik, 2011c). If solar activity remains at the modern (present) level for 1 My and 100 My, respectively, we may expect 6×10^6 and 6×10^8 of such events, and their occurrence probabilities would be $\sim 1.7 \times 10^{-7}$ and $\sim 1.7 \times 10^{-9}$, respectively. According to our estimates (Fig. 9), for these long periods, the events may appear with fluences of up to 6×10^{10} and $10^{11}\ \mathrm{cm}^{-2}$, respectively, which is 1.5 $\div$ 2 orders of magnitude lower than the estimates of Kiraly and Wolfendale (1999). The two triangles in Fig. 9 depict our estimates for $\Phi(\geq 30\ \mathrm{MeV})$ based on the data of Kiraly and Wolfendale (1999) for proton fluences at energies $\geq$60 MeV and extrapolated into the past for 1 My and 100 My. The difference in the energies of the protons (30 and 60 MeV) makes this discrepancy even greater.

The cause of this discrepancy is rather simple. As has been repeatedly noted (Nymmik, 2006, 2007a,b, 2011a,b,c), the lognormal distribution function of SEP events (Feynman et al., 1993) that was applied by Kiraly and Wolfendale (1999), by no means reflects the physical essence of the SEP event distribution in the range of large fluences. The parameters of the model by Feynman et al. (1993) are determined mainly by the subjective (random) magnitudes of the registration thresholds and the selection of small SEP events; therefore, they cannot serve for the extrapolation of the data into the range of extremely large events.

6. Summary and conclusions

The present work has been accomplished with new methodological procedures whose application has become possible because of the accumulation and/or appearance of new observational data concerning SEP fluxes and fluences. Our main result is that a form of the SEP distribution function that was previously obtained from fluence data for three cycles of SA has been completely confirmed by the data for approximately 41 solar cycles. In summing up this study, we confine ourselves to only a few concluding remarks.

1. First of all, a considerable extension of the energy range has been achieved for the measured particle fluxes – from 0.32 to 500 MeV (sometimes to $\geq$10 GeV) for protons and from 0.035 to 168 MeV/nucleon for heavy ions (e.g., for Fe ions).
2. Another important factor proved to be the appearance of substantially new data from SEP events in the past, namely, from large SEP events for the period of 1561–1950, that have been obtained from the Greenland ice cores; of particular interest among them is the extreme large Carrington event of 1859.
3. Additionally, in our study we were guided by the modern concept of the upper-limit spectrum (ULS) for solar cosmic rays. This allowed us to revise and confirm our previous semi-empirical ideas regarding the true form of the SEP energy spectra at the Earth's orbit: in a limited energy range, they may be approximately described by double power-law functions separated by "a knee."
4. Combination with the ULS enables us to develop a new approach to the "worst-case" concept, and the Carrington event provides a crucial normalization point for this goal. This prospect seems to be very promising for the modeling and for the calculation of radiation doses.
5. It should be recognized, however, that if one attempts to analyze the problem in more refined way, it is also necessary to take into account the possibility to vary the form of the SCR spectrum from the very moment of their release from the source(s) (see Fig. 3 above). Indeed, by the time that near-Earth measurements are made, the knee positions (break-points) in the individual events may be dependent on the particle energy and the SEP event size. In particular, according to observations of SEP events in December 2006 with the Low Energy Telescope (LET) on *STEREO* (Mewaldt et al., 2009), all the proton spectra exhibit spectral break-points at energies ranging from $\sim$2.4 to $\sim$33 MeV and all are well fit by a double power-law shape (see also Nymmik, 2011a and Fig. 4 of the present work).
6. At the same time, significant differences in the values of power-law index γ may occur for protons in non-relativistic SEP events depending on whether they are followed by relativistic GLEs. In fact, the only significant difference was found in the spectral index above the spectral break in the proton spectrum (typically $\geq$30 MeV for protons), which is -3.17 for GLEs, and -4.34 for non-GLEs. This harder spectrum allows smaller SEP events to supply many more protons with energy >0.5 GeV (cf. Fig. 3) using the same amount of energy from the solar accelerator as is measured in larger events. This does not contradict the fact that there is a single distribution of SEP events in terms of their spectral indices in the energy range above the break-point energy E_b. This distribution does not depend on the event size. It is natural that a GLE takes place only in the large SEP events in which the spectra are hard, i.e., the absolute value of γ for the GLE case is less than average value.
7. Thus, we have identified a number of physical and methodological limitations that are important for the estimation and prediction of hazardous SCR radiation fluxes. Our technique, which was developed on the basis of new ideas regarding

particle fluxes and their intrinsic features, also enabled us to consider anew the problem of “limit” values that characterize SEP fluxes at different energies in the present epoch. At the same time, we do not pretend to give final values of our quantitative estimates which can yet be refined as new observational data become available.

Added in proof

Quite recently, based on some indirect but totally independent data, we have encountered a good opportunity to verify our new methodological approaches and results. Miyake et al. (2012) have published the results of their ^{14}C measurements (the so-called carbon-14 method) in the annual rings of Japanese cedar trees from AD 750 to AD 850 with 1 and 2 year resolutions. A rapid increase of approximately 12% in the ^{14}C content from AD 774–775 was found, which is approximately 20 times larger than the change that can be attributed to ordinary solar modulation. The authors, however, argue that neither a solar flare nor a local supernova is likely to have been responsible for this increase. Meanwhile, the reality of the AD775 event is confirmed with the new measurements of ^{14}C content in the German oak (Usoskin et al., 2013). These authors, on the contrary to Miyake et al. (2012), argue in favor of that this event could be associated with a strong, but not inexplicably strong, SEP event (or a sequence of the events).

However that may be, researchers from another group (Thomas et al., 2013) have decided to examine possible sources of this substantial increase of ^{14}C content in AD 774–775. First of all, the authors rejected a coronal mass ejection (CME) as a possible cause of the effect because the required CME energy is not several orders of magnitude greater than known solar events. They proceeded to model solar proton events (SPEs) with three different fluences and two different spectra. Finally, they concluded that the data can be explained by an event with a fluence approximately one order of magnitude (a factor of approximately 7 or more) greater than the SPE of October 1989 (depending on the spectrum). Two hard spectrum cases considered by Thomas et al. (2013) may result in moderate ozone depletion, so no mass extinction is implied. At the same time, the authors do predict increases in erythema and damage to plants from the enhanced solar UV. Additionally, they are able to rule out an event with a very soft spectrum that causes severe ozone depletion and subsequent biological impacts. As for the nitrate enhancements expected in the period under consideration, they seem to be consistent with the apparent absence of such an effect in ice-core data.

Turning now to the data of October 1989, it should be emphasized that, in fact, three separate SPEs have been registered during that time (on 19, 22, and 24 October), with $\Phi(\geq 30$ MeV) values of approximately 1.82×10^9, 7.44×10^8, and 3.95×10^8 cm^{-2}, respectively (e.g., Nymmik, 1999c). The sum of these values yields a total fluence of $\Phi(\geq 30\ \text{MeV}) = 2.96 \times 10^9$ cm^{-2}. This value, obviously, cannot compete with that for the Carrington event, 1.88×10^{10} cm^{-2}. However, when multiplying the total fluence for the three events of October 1989 by a factor of $7 \div 10$ (Thomas et al., 2013), we obtain the values of $\Phi(\geq 30\ \text{MeV}) = (2.07 \div 2.96) \times 10^{10}$ cm^{-2} which are comparable to the CE fluence. As for the integral flux of the protons $F(\geq 30$ MeV), its expected value for the event of AD 774–775 lies just down the ULS curve (Fig. 8) when we multiply the corresponding flux value for the event of 19 October 1989 by the same factor of $7 \div 10$.

Note that in the case of the Carrington event we are dealing with real experimental data, whereas for the event of AD 774–775 all estimates are model dependent. On the other hand, the modern technological implications of such events may be extreme. Considering the recent confirmation of super-flares on solar-type stars, this issue merits attention.

Acknowledgments

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